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Integrated process modeling for the laser inertial fusion Energy (LIFE) generation system

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Abstract. A concept for a new fusion-fission hybrid technology is being developed at Lawrence Livermore National Laboratory. The primary application of this technology is base-load electrical power generation. However, variants of the baseline technology can be used to “burn” spent nuclear fuel from light water reactors or to perform selective transmutation of problematic fission products. The use of a fusion driver allows very high burn-up of the fission fuel, limited only by the radiation resistance of the fuel form and system structures. As a part of this process, integrated process models have been developed to aid in concept definition. Several models have been developed. A cost scaling model allows quick assessment of design changes or technology improvements on cost of electricity. System design models are being used to better understand system interactions and to do design trade-off and optimization studies. Here we describe the different systems models and present systems analysis results. Different market entry strategies are discussed along with potential benefits to US energy security and nuclear waste disposal. Advanced technology options are evaluated and potential benefits from additional R&D targeted at the different options is quantified.

1.0 Introduction

Fusion-fission hybrid technology based on Laser Inertial Fusion Energy (LIFE) is being developed at Lawrence Livermore National Laboratory. The primary application of this technology is base-load electrical power generation using energy multiplication in a fission blanket with depleted uranium (DU) as the beginning of life heavy metal (HM). An integrated process model (IPM) for a LIFE power plant has been developed that includes cost and performance algorithms for the major subsystems of the plant, including the laser, fusion target fabrication, fusion-fission chamber (including the tritium and fission fuel blankets), heat transfer and power conversion systems, and other balance of plant systems. The model has been developed in Visual Basic with an Excel spreadsheet user interface in order to allow experts in various aspects of the design to easily integrate their individual modules and provide a convenient, widely accessible platform for conducting the system studies. In this paper we describe key aspects of the IPM and report on the results of our systems analyses for a particular design based on indirect-drive, hot-spot ignition (HSI) targets and a fission blanket using depleted uranium fuel. The cost of electricity (COE) is used as the figure of merit for design optimization and to reveal key cost and performance sensitivities. Additional details on the LIFE plant are given in Refs. 1-5.

2.0 Integrated process model (IPM)

The integrated process model (IPM) includes detailed cost and performance models for the major subsystems of the power plant. Key features are summarized here with a more detail description of the model presented in Ref. 6.

Laser system capital costs are scaled from NIF project costs, with adjustment for N'th of a kind costing, diode pumping, active cooling and a more compact architecture. NIF is a one-of-a-kind R&D facility whereas this paper is addressing an N'th-of-a-kind power plant. NIF unit costs have been adjusted to give credit for future manufacturing learning, account for non-recurring costs, such as supply chain development, and adjusted for beam line architecture differences between NIF and a LIFE power plant. Additional costs for systems needed for high pulse rate operation, such as the diodes and power conditioning, and active cooling are added to arrive at the total LIFE laser cost.

Target costs are based on a conceptual design of an automated target production facility (target factory) including estimates for buildings, process equipment, fixed and variable operating and maintenance costs. The sum of the annual capital-related charges, operation and maintenance (O&M) and feed materials gives a unit cost of \$0.25/target. For a plant operating at 10 Hz and a capacity factor of 85%, 2.7×10^8 targets are needed per year resulting in an annual target cost of ~\$67M.

The costs for the nuclear island (NI) and balance of plant (BOP) are derived various fission reactor studies [7,8]. The LIFE plant is similar to the liquid metal reactor in that neither technology requires the high pressure containment systems and structures typical of light water reactors, but both require intermediate coolant loops. Costs for the LIFE fusion target chamber and vacuum vessel, which are very different from a nuclear reactor pressure vessel, are calculated directly based on estimated raw material costs and an assumed fabrication cost multiplier. Additional allowances are included for LIFE unique systems such as tritium recovery, storage and special materials such as the molten salt coolants.

We have adopted the approach as reported in the MIT study for calculating the COE [9,10]. The power plant project is assumed to be financed with a combination of equity and debt financing yielding a nominal, tax adjusted cost of money of 7.8%. Annual costs are summed (accounting for the benefits of accelerated depreciation) and then deflated to 2007 dollars. This results in an effective fixed charge rate on capital investment of ~7.7%. The overnight construction cost, accounting for home and field office engineering, owners cost, etc. increases the direct capital cost by 59%. At this point we are assuming a uniform 10%, across the board contingency. Interest during construction is based on a 5 year construction period and increases the capital investment by ~10% (in 2007\$). Therefore the total capital cost (in 2007\$) is ~1.9 times the direct capital cost. In calculating the COE we assume a constant plant availability of 85%.

3.0 Base case results

As a point of comparison, we have selected a nominal base case design. The laser energy on target is 1.86 MJ and produces a target yields of 51 MJ (target gain = 27). The overall energy multiplication in the tritium breeding and fission blankets (including fission product decay heat) is 5.35, so at 10 Hz, the thermal power is 2690 MW_t. The molten salt coolant with outlet temperature of 650 C drives a Brayton power cycle with a thermal conversion efficiency of 46%, generating 1234 MW_e gross electric power. The 9.5% efficiency laser requires 196 MW_e and we assume that 3% (37 MW_e) of the gross electric is required for in-plant auxiliary power needs. The plant net power is 1000 MW_e.

The COE for this design is ~\$65/MWh (i.e., 65 mils/kWh). The top-level contributions to the COE are: capital 69%; operations and maintenance (O&M), 17%; and fuel, 14%. The contributions to the capital cost (\$4.2B total) are: power block (chamber, heat transfer system and power conversion system), 40%; balance of plant, 34%; laser, 18%; and special materials (e.g., molten salt), 8%.

4.0 Results for other LIFE options and other base-load technologies

Figure 1 gives COE results for three other LIFE designs: a design using a fissile blanket with a higher fission blanket gain, a pure fusion design, and a pure fusion design with a fast ignition target. All are designed to produce 1000 MWe net power. COEs are all within 10% of the base case LIFE with a DU

blanket. The COEs for pure fusion designs are competitive because we have assumed a 20% cost savings in the balance of plant and a higher thermal conversion efficiency (50% vs. 46%) expected without the fission blanket.

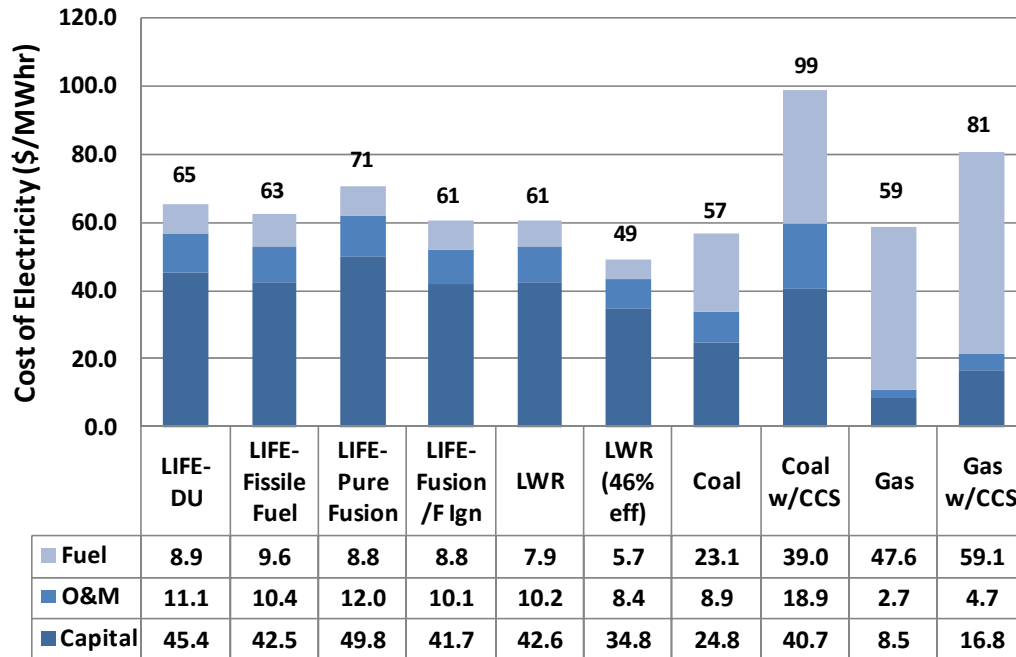


Figure 1. Comparison of LIFE to alternative base-load technologies.

We also show other technologies including a LWR, fission with higher conversion efficiency, and coal and gas, each with and without carbon sequestration. We conclude that LIFE costs compare favourably with other carbon-free base load technologies.

5.0 Design Space Studies

Next we examine the COE as a function of target yield, rep-rate and net electric power.

Figure 2 shows the COE as a function of rep-rate for net powers of 1000, 1300 and 1600 MW_e. At each point, the laser energy and target yield are adjusted to keep the net power fixed. As indicated, the COE is relatively insensitive to rep-rate with 5-10 Hz near optimal for all three power levels. Larger plants have significantly lower COEs reflecting more economical use of the capital investment in the laser and the economy of scale benefits of the larger nuclear island and BOP.

Figure 3 shows the COE as a function of target yield, again for three net electric powers. At very low yields, the target gain is low and the laser recirculating power is high, resulting in a high COE. COE decreases with increasing yield, with yields in the range of 50-75 MJ near optimal for this range of plant sizes. The markers on each line correspond to rep-rates of 20, 15, 10 and 5 Hz moving from left (low yield) to right.

6.0 Summary

We are developing LIFE as a carbon-free, base-load power technology that with adequate R&D funding and successful development of key technologies could enter the commercial market ~2030. The LIFE Integrated Process Model is being used to guide conceptual designs to attractive operating space and to identify high leverage R&D. Scoping-level cost estimates indicate that LIFE can be competitive with fission power and fossil plants with carbon sequestration. Large plants (>1000 MW_e)

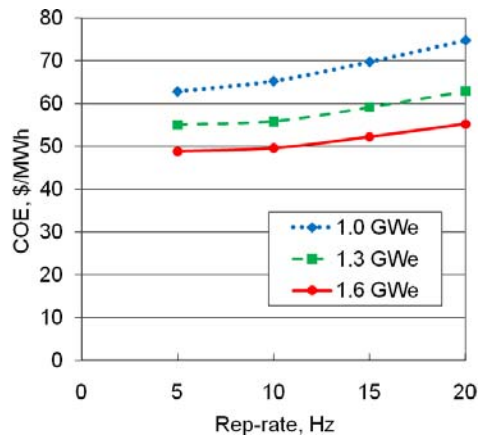


Figure 2. COE vs. rep-rate for net powers of 1.0, 1.3 and 1.6 GWe.

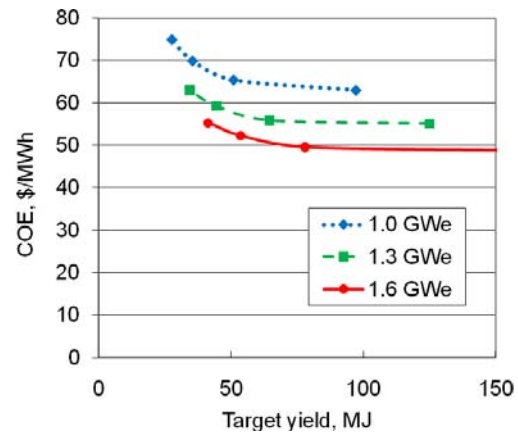


Figure 3. COE vs. target yield for net powers of 1.0, 1.3 and 1.6 GWe.

are most cost effective. Fission blanket energy multiplication allows operation at modest target yields (~50-75 MJ), reducing required laser energy and cost. The COE is relatively insensitive to rep-rate for fixed net power and rep-rates of ~10 Hz or less are optimal. With estimated cost reductions relative to NIF, laser capital cost is only ~17% of the LIFE plant capital cost. Assuming LIFE nuclear island and BOP costs are similar to fission plants, they account for 74% of total capital cost. We are now pursuing innovative lower-cost, high-efficiency laser architectures and higher-temperature, high efficiency chamber concepts to optimize the economics of LIFE.

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